Preliminary opto-mechanical design for the X2000 transceiver

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ABSTRACT

Preliminary optical design and mechanical conceptual design for a 30 cm aperture transceiver are described. A common aperture is used for both transmit and receive. Special attention was given to off-axis and scattered light rejection and isolation of the receive channel from the transmit channel. Requirements, details of the design and preliminary performance analysis of the transceiver are provided.

Keywords: Optical communication, optical design

1. INTRODUCTION

A transceiver is designed for communication from the range of 6 AU to ground. The host spacecraft is of the type developed under the X2000 technology development program. A description of this program is given in Reference (1). The operation of the transceiver consists of tracking a laser beacon from the earth or the sun-illuminated earth image beacon, and transmitting a signal back to the ground station.

To minimize coordinate transfer errors between the tracking and transmit channels, and to minimize the size and complexity of the transceiver, the same aperture is used for both transmit and receive signals. An optical block diagram for the transceiver is shown in Figure 1. For laser beacon tracking the transmit and receive signals differ by 532 nm. However, for extended-source earth image tracking the broad-band spectrum of the sun overlaps the 1064 nm laser transmit wavelength. This design is based on the Optical Communication Demonstrator (OCD) architecture. An overview of the OCD instrument can be found in Reference 2. The optical system consists of four optical channels.

1. **Transmit Channel.** This channel consists of an optical path to relay a transmit signal from the output of the laser transmitter to the exit aperture of the optics. The transit optical path must provide fine-pointing capability to control the downlink over the entire system field-of-view. The transmit path must maintain good beam quality over the entire field-of-view.

2. **Data Detector Receive Channel.** This channel consists of a receive optical path to collect the incident photon from the input aperture to the data detector. The receive optical path must provide narrow-band filtering to reduce the amount of background radiation, and must provide the field-of-view necessary to cover the spacecraft deadband cycle. Furthermore, the receive optical path must provide sufficient isolation such that the effect of signal feedback from the transmit path is minimized. Wavefront quality is not essential for the receive path. However, matching a wide field-of-view to a small diameter detector poses significant challenges to the optical design.

3. **Tracking Receive Channel.** This channel consists of an optical path that images the field-of-view onto the celestial reference detector. This detector is currently baselined to be a 1024x1024 array with 20 micron pixel size, and covers the 9 mrad x 9 mrad field-of-view. The receive optics should provide intentional blurring of the image to spread the tracking signal over 2-3 pixels. However, it must be void of coma and other non-symmetric aberration patterns.

4. **Tracking Reference Channel.** This channel consists of a tracking reference path that images the transmit signal (after the fine-pointing mirror). This tracking reference measures the instantaneous position of the downlink signal. This design differs from that of the OCD where a signal detector array is used for celestial reference and for tracking reference because of concerns over the tracking signal dynamic range. Over the large distances expected, and particularly when earth image tracking is required, the dynamic range of the tracking signal can vary by 2-3 orders of magnitude. A single detector for both references will therefore need to operate over different frame rates for the two signals. Current CCD and APS technology do not permit such devices to be implemented. Consequently, the approach taken is to provide a separate imager that images the tracking reference signal.

The relative position of the two images (tracking and reference) on the detector is used to accurately aim the transmit signal at the ground station. Because of the round-trip time between the spacecraft and the ground station, the transmit signal must be pointed ahead (or behind) the apparent position of the ground station. Since the host spacecraft has the capability to locate earth and maintain its pointing attitude to earth within a few mrad, the initial acquisition and coarse pointing of the transceiver is achieved using the spacecraft itself. Precise pointing of the transmit signal is achieved using a two-axis fine-pointing mirror in the transmit channel. By observing the position of the beacon image on the focal-plane-array detector relative to the reference location for the center of the receive channel, the fine-pointing-mirror can be used to correct the aiming of the transmit channel towards the ground station. The aiming of the transmit channel is indicated by the position of the tracking signal image on the detector relative the reference location for the center of the tracking reference channel.

2. OPTICAL SYSTEM REQUIREMENTS AND DESCRIPTION

The major optical requirements for the transceiver and corresponding desired values are shown below. The field of view in the transmit channel and the Reference channel is relatively small and is mainly driven by the movement of the fine-pointing mirror. The field of view in the receive channel is larger and is determined by the size of the area detector.

Parameter		Value
Transmit	Aperture (cm)	30
	Wavelength (nm)	1064
	Channel Efficiency	> 70%
	Field-of-View (FOV, Deg.)	± 0.28
	Beam Quality (Strehl)	> 0.8 (over FOV)
	Channel Beam Vignetting (% Area)	> 70%
Receive	(ACQ/TRK) Channel aperture (cm)	30
	Effective Focal Length (cm)	150
	Focal Ratio	f/5.0
	Wavelength (nm)	550 - 1000
	FOV (°)	±2.8
	Efficiency (%)	> 40%
	Image Quality (Strehl)	> 0.9
Receive	(Data) Channel wavelength (nm)	532
	Focal Ratio	1 (approx.)
	FOV (°)	± 0.28
Reference	Channel wavelength (nm)	1064
	Fine-pointing Mirror Angle (°)	± 3.4
	Performance (Strehl)	> 0.7

3. OPTICAL DESIGN APPROACH

An optical block diagram of the transceiver is shown in Figure 1. Both Ritchey-Chretien (RC) and Gregorian telescope type designs were carried out to preliminary stages. The RC telescope was selected for detailed design since a smaller telescope could be made and baffling of the telescope optics is simpler. The restriction on the overall size of the transceiver resulted in relatively fast optics for the telescope. Length of the acquisition and tracking receive channel optical system was kept short by using a relatively high telephoto ratio of about three to one. All optical elements have either flat or spherical optical surfaces except for the two telescope mirrors which are both hyperbolic.

Some of the design drivers and design practices are listed below:

1. Short focal length primary mirror: the requirement for short telescope length limit the F/# of the telescope primary mirror to about F/1.0. Because the overall focal length at the Acquisition detector must be 1.5 m, a large secondary magnification is required. The large magnification results in significant field curvature, which must be corrected for auxiliary optics.

2. Field-of-view: the field of view requirement of $\pm 0.28°$ is relatively large for a two-mirror telescope optical system. Residual aberrations are astigmatism and curvature of the field, which must be corrected by the auxiliary refractive optics. That makes the auxiliary optics design more complicated. It requires more optical elements.
3. Field-stop: a field-stop is required due to concern about the presence of bright objects (such as the sun) near the edge of the field of view in the telescope. In addition, because of diffuse scattering from the telescope mirror surfaces, only a maximum of two mirror surfaces is allocated before the field stop. This means that astigmatism and field curvature will not be corrected in the telescope and must be corrected by the auxiliary optics.
4. Well-baffled telescope: rays directed around the baffles to any where inside the field-stop must be blocked-off before going through the telescope aft optics
5. Lyot stop: the Lyot stop is needed to eliminate diffracted energy from bright out-of-field objects like the sun. The Lyot stop is an image of the entrance aperture of the optical system. It is also a conjugate near-field point. Two such conjugate near-field points or images are required: one at the fine-pointing mirror and one at some other point in the optical system. The one at the fine-pointing mirror is required to assure that there will be no beam walk at the primary mirror when the mirror is moved for fast pointing purposes. The other near-field point image is needed for a Lyot stop to block out of field radiation that is diffracted into the field of view by the edges of the two telescope mirrors, baffles, spider vanes, etc. Providing a second near-field point for a Lyot stop will require additional imaging and collimating optical elements. These additional optical elements will make the optical system larger and more complex. Currently, a near-field point for a Lyot stop is not available in the design.
6. Spectral band-pass: the spectral band pass is equal to one octave. The broad band requirement of 532 nm to 1064 nm is difficult to achieve with anything but refractive optics. An all refractive design was proved much more difficult to produce while maintaining a small transceiver volume.
7. Multiple redundant optical channels: The requirement for multiple and redundant optical channels requires a long optical path in the auxiliary optical system. Providing this optical path for beam-splitting is most easily achieved using refractive optics. However, beam-spread away from a near-field point due to the field-of-view derives the size of these optical elements up. In other words, the larger field-of-view, along with the numerous beam-splitters required, make the auxiliary optics path length long and the overall optical system large.
8. Radiation environment: The radiation environment is a problem for the design of the refractive portion of the optical system. The number of optical glasses available that are radiation resistant is small. There are about a dozen glasses that have suitable optical and mechanical characteristics. The small number of glasses available makes it difficult to properly correct the chromatic aberration over the required spectral range of 532 nm o 1064 nm.

It was estimated that about 130 dB isolation of the receive channel from the transmit channel is required. The design utilizes high reflectance laser wavelength beam-splitter for the main beam-splitting function along with high attenuation spectral filters in the data and acquisition and tracking channels.

Specular backscatter from flat transmitting surfaces that are normal to the incident beam could cause actual ghost images at the detector array. This means that the backscattered energy would be concentrated over just a few pixels. To eliminate this possibility, the flat transmitting surfaces will be tilted so that any ghost images will fall outside the detector array field-of-view. The curved refracting surfaces will also cause specular backscatter. However, the backscattered energy will be very low at the detector array since the focal point for the backscattered energy will be far from the detector.

The most likely sources of unwanted radiation at the various focal planes in the optical system and our mitigation approach are as follows:

1. Scattered sunlight from optical surfaces due to surface roughness and contamination. Direct sunlight will first strike the two optical surfaces of the transceiver telescope optics.

2. Scattered sunlight from mechanical surfaces such as baffles, aperture edges and spider vanes. Because the transceiver must point near the sun, sunlight will strike these surfaces.

3. Diffracted sunlight from the telescope baffles, aperture edges and spider vanes. Even though sun will be outside the field-of-view of the transceiver, some sunlight could be scattered into the field-of-view by high order diffraction.

The first source of stray light will be minimized by keeping the optical surfaces as clean as possible and by making them very smooth (on the order of 1 nm RMS). It is expected that the total integrated scatter due to surface roughness and contamination at each surface will be 3E-04 or less.

The second and third sources of stray light will be minimized by using good baffle design along with a field-stop and Lyot-stop. The Lyot stop will be located at the near-field point and designed so that no baffle, spider vane or optical element edges ahead of the telescope focal plane can be seen at any of the detectors. The Lyot stop and the field-stop together will assure that no radiation from outside the field-of-view can be imaged or diffracted into the field-of-view at any detectors.

It is expected that the above approach will result in less than 1E-18 of the incident radiation on the transceiver from the sun will fall on any single detector pixel. This is an adequate level of isolation and needs to be verified by actual scattered and stray light analysis.

4. OPTICAL SYSTEM PERFORMANCE

Features of the optical system include: 30 cm aperture; F/1.0 telescope primary mirror; redundant data detectors; redundant acquisition and tracking detectors; redundant laser transmitters; field stop and Lyot stop; super smooth telescope primary and secondary mirror surfaces to minimize forward surface scattering; laser insertion point in front of the Lyot stop; and cube type beam-splitters to minimize polarization and to maximize the transmittance. They will be cemented together where possible that minimizes air to glass interfaces. Also, this minimizes alignment drift.

Figure 2 shows a Point-Spread-Function (PSF) of the Transmit channel including the effect of the secondary obscuration. The PSF shows that the transmit channel has a diffraction-limited performance and most of the energy is in the Airy disk.

The computed effective transmittance of each channel, based on individual surface values, is summarized below:

Transmit Channel Transmittance (1064 nm)	0.71
Acq/Trk Channel Transmittance (540-900 nm)	0.24
Data Channel Transmittance (532 nm)	0.15
Reference to Acq. Trk Channel Transmittance (1064 nm)	7.7E-14
Reference to Data Channel Transmittance (1064 nm)	4.2E-17

The effective transmittance for the Reference channel and the Data channel, and the Reference to the Acquisition and Tracking channel is the effective transmit/receive isolation for each one. However, these values do not include possible diffuse and specular backscatter from optical surfaces ahead of the main backscatter. All surfaces between the primary mirror in the telescope and the main beam-splitter coating can cause either specular and/or diffuse backscatter. A preliminary calculation has been performed to evaluate these backscatter possibilities. The results are as follows:

Diffuse laser backscatter to Data Channel (1064 nm)	4.2E-20
Diffuse laser backscatter to Acquis. and Track. Channel (1064 nm)	3.8E-18
Specular laser backscatter to Data Channel (1064 nm)	1.0E-18
Specular laser backscatter to Acquisition & Track. Channel (1064 nm)	9.2E-16

These backscatter values represent the fraction of transmitted laser radiation that could be scattered back into the total field of view of the area array. The amount of light scattered into an individual pixel would be diminished by a factor equal to the reciprocal of the number of pixels in the array.

5. MECHANICAL AND MATERIAL

Figure 3 shows the mechanical mounting concept for the transceiver. The aft-optics path is folded such that the sensors and the laser head may be mounted in one or at the most two planes behind the telescope. This will result in substantial size reduction of the opto-mechanical assembly. The telescope and optical structure material need to have very low thermal expansion, high thermal conductivity and low weight. Currently, the SiC material is baselined for the telescope (structure, primary and secondary mirrors) material. The properties of SiC that makes it attractive for the space optics applications include: (1) high specific stiffness & low mass; (2) very low thermal expansion coefficient (on the order of 1 ppm/K); (3) high thermal conductivity; (4) very high bending strength (400 Mpa) and low built in stress (< 0.1 Mpa); (5) it can withstand low and high temperatures without any loss of properties; (6) tests have shown that it is very insensitive to fatigue; (7) very high immunity to radiation; and (8) it can be easily ground and polished without distortions. Raw surface roughness is less than 0.5 mm and fine grinding can reduce it below 0.1 mm. SiC is polishable with a convergence as good as glass. Surface roughness can be as low as 1 nm.

6. SUMMARY

A compact transceiver for optical communication from deep-space was designed and analyzed. Diffraction limited performance was achieved in all four channels. The optical design adequately addresses the requirements for off-axis sun-light and scattered light rejection, as well as isolation of the receive channel from the transmit channel. The host platform for the optical communication terminal has changed from the X2000 First Delivery to X2000 Second Delivery. The latter will be a much smaller size spacecraft. Thus, the transceiver design described above is now continuing for a smaller (10 cm) aperture and with no redundancy of the subsystems.

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REFERENCES

1. Hemmati and J. R. Lesh "Laser Communication terminals for the X2000 Series of Planetary Missions," Proceedings of SPIE, V. 3266, 171-177, San Jose, CA (1998).

2. Chen and J. R. Lesh, "Overview of the Optical Communication Demonstrator," Proceedings of SPIE, Vol. 2123, Los Angeles, CA, January 1994.

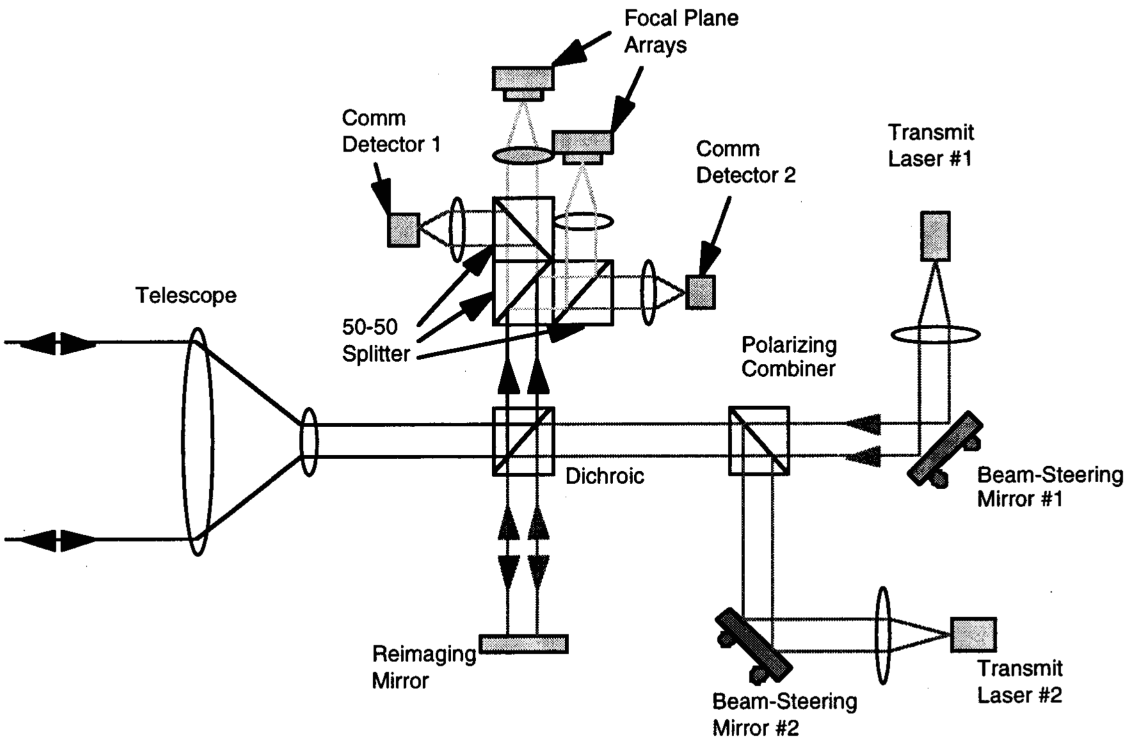

Figure (1). Block Diagram of the Optical Communication Transceiver Showing the Redundant Subsystems

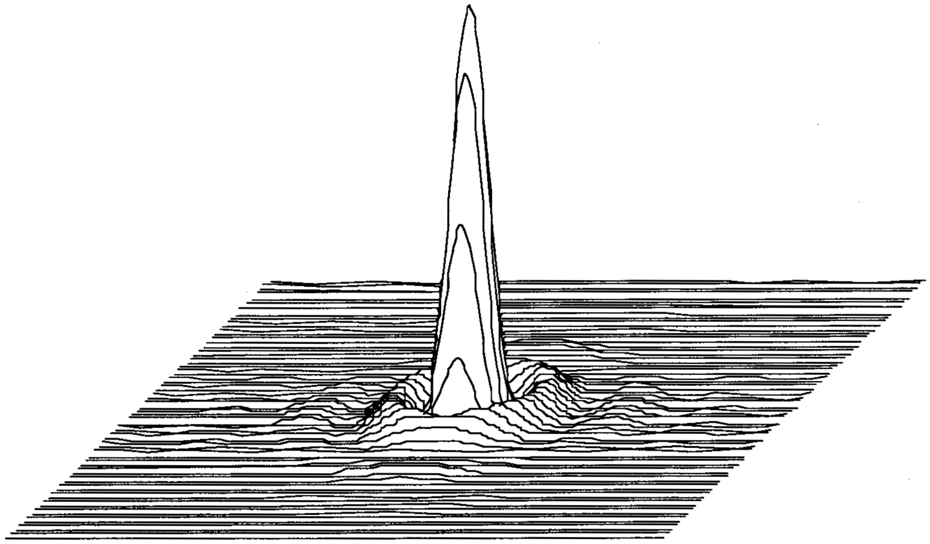

Figure (2) Point-Spread Function of the Transmit Channel with & without Secondary Obscuration

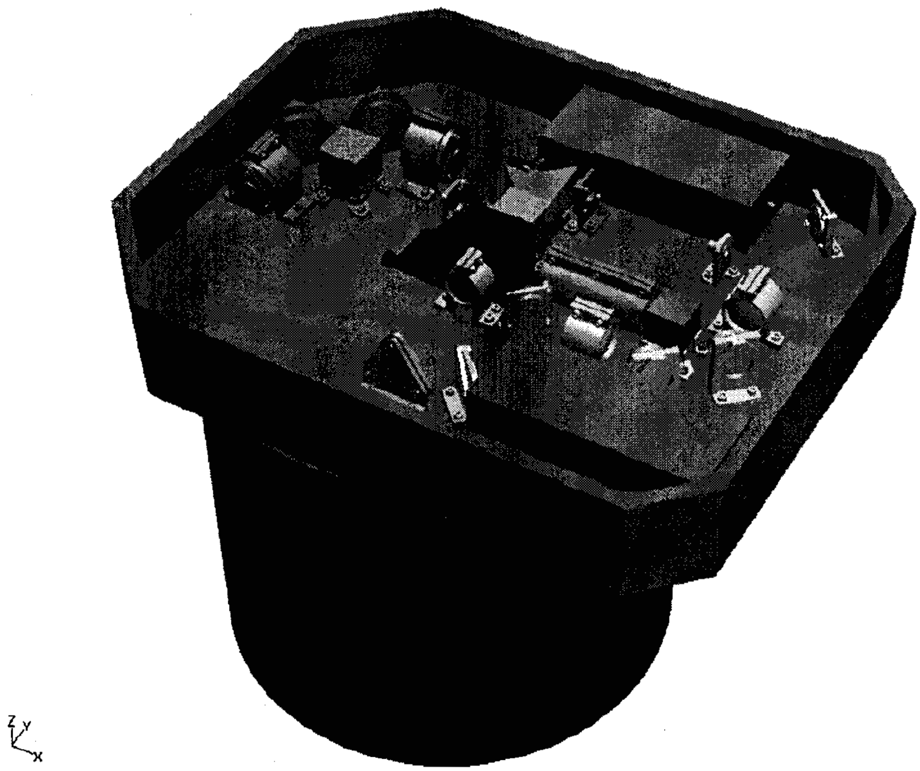

Figure (3). Mechanical Structure Concept for the Transceiver